Initial stage jet momentum broadening in tBLFQ formalism

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Motivation of this work

Some studies suggest that $\hat{q}$ must be **suppressed** in the initial stage of heavy ion collisions [Phys. Lett. B 803 (2020) 135318]

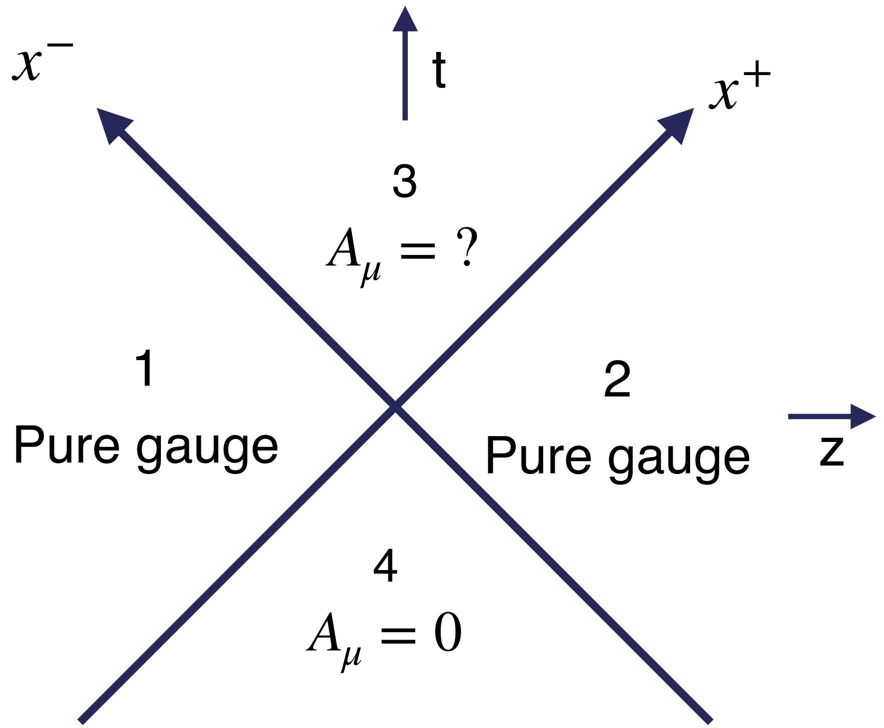
Classical jet analysis show that in fact $\hat{q}$ is **very large** [Phys. Lett. B 810 (2020) 135810]

See Florian's talk for more information about this puzzle

See Andrey's talk for an analytical calculation of jet quenching in Glasma

We perform for the first time a complete **quantum treatment** of the jet interacting with the **classical Glasma fields** using tBLFQ, a light-front Hamiltonian formalism

The Glasma fields



$$x^+ = x^0 + x^3$$

$$x_+ = \frac{1}{2}(x^0 - x^3)$$

In the regions (1) and (2) nuclei are modeled using **Color Glass Condensate**

Collision

See Dana's talk for more information about the Glasma fields

Boost invariant **Glasma fields** in region (3)

[Phys. Rev. D **52**, 6231]

We evolve them numerically solving the **free Young-Mills** equation $[D_\mu, F^{\mu\nu}] = 0$ using **real-time lattice gauge theory**.

The natural gauge for the Glasma fields is **Fock-Swinger temporal gauge**

$$A_\tau = \frac{x^+ A_+ + x_+ A^+}{\tau} = 0$$

The time-dependent Basis Light-Front Quantization (tBLFQ) formalism

Exploit the QFT <-> QM similarities in **LC quantization**

Construct the eigenstates of the Hamiltonian using BLFQ

[Phys. Rev. C 81 (2010), 035205]

Make the states evolve under the action of the external field

$$|\psi; x^+\rangle_I = T_+ e^{-\frac{i}{2}\int_0^{x^+} V_I} |\psi; 0\rangle_I$$

[Phys. Rev. D 88 (2013) 065014]

Successfully applied to $|q\rangle$ and $|q\rangle + |qg\rangle$ evolution in a **MV model field**

[Phys. Rev. D 101 (2020), 076016] [Phys. Rev. D 104 (2021), 056014] [Phys.Rev.D 108 (2023) 3]

The method is based in light-front Hamiltonian formalism, and the light-front Hamiltonian is derived from the QCD Lagrangian in a **light-cone gauge**

Gauge transformation of the fields

The Glasma and jet evolution have different natural gauges

Glasma $\longrightarrow A_\tau = 0$ gauge **Jet** $\longrightarrow A^+ = 0$ gauge

To use tBLFQ we need to **gauge transform** the Glasma gauge links to LC gauge

We construct the gauge transformation in a **discretized way** in real-time lattice gauge theory **using the gauge links obtained from the Glasma simulation**

We work in **eikonal approximation**, so only the A_+ component of the fields has to be transformed and the jet has no diffusion in transverse position space

Mid-rapidity approximation

We only consider jets at **small z:** $t \sim \tau$; $A^+ = \frac{1}{\sqrt{2}}(zA^\eta + A^x)$

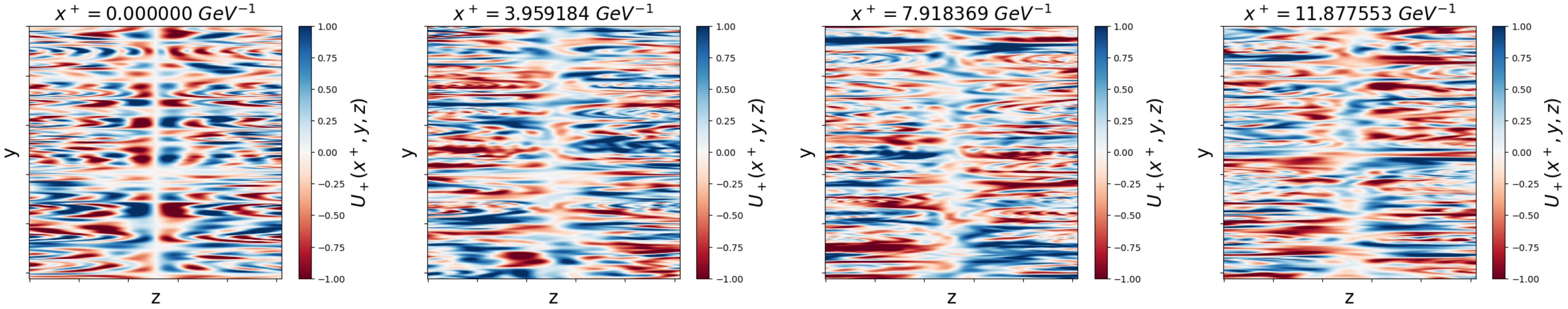
Should we require the fields to vanish when z > t?

Excludes unphysical points outside the Glasma light-cone, but it is not consistent with the approximation $\tau \sim t$

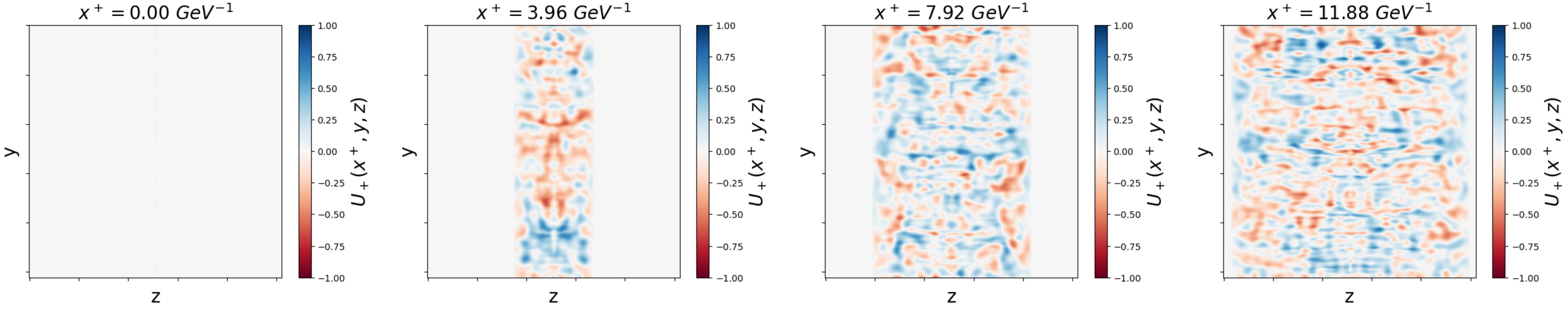
Results should be **independent of this condition** as our jet should only be sensitive to the fields at very small z

The Glasma fields in LC gauge

Not setting the field to 0 when $z > t$

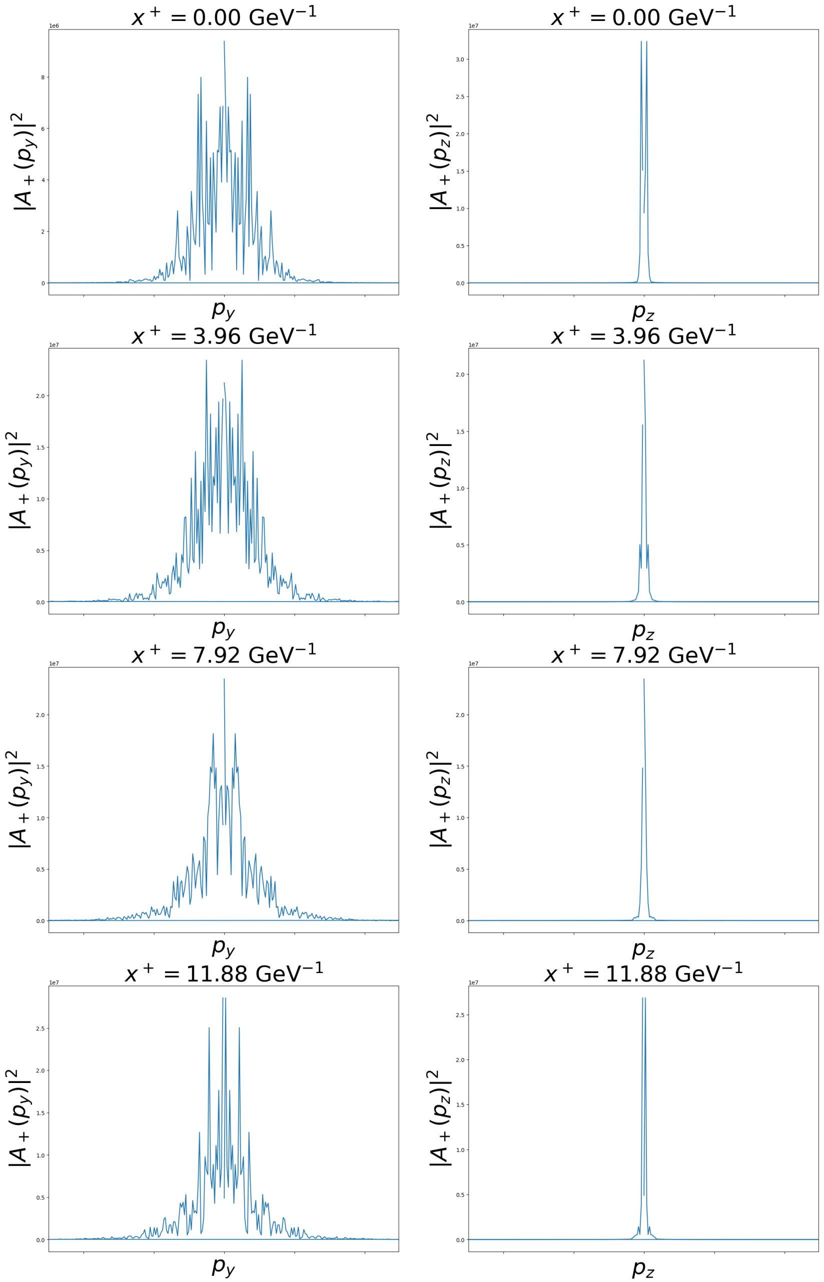


Setting the field to 0 when $z > t$

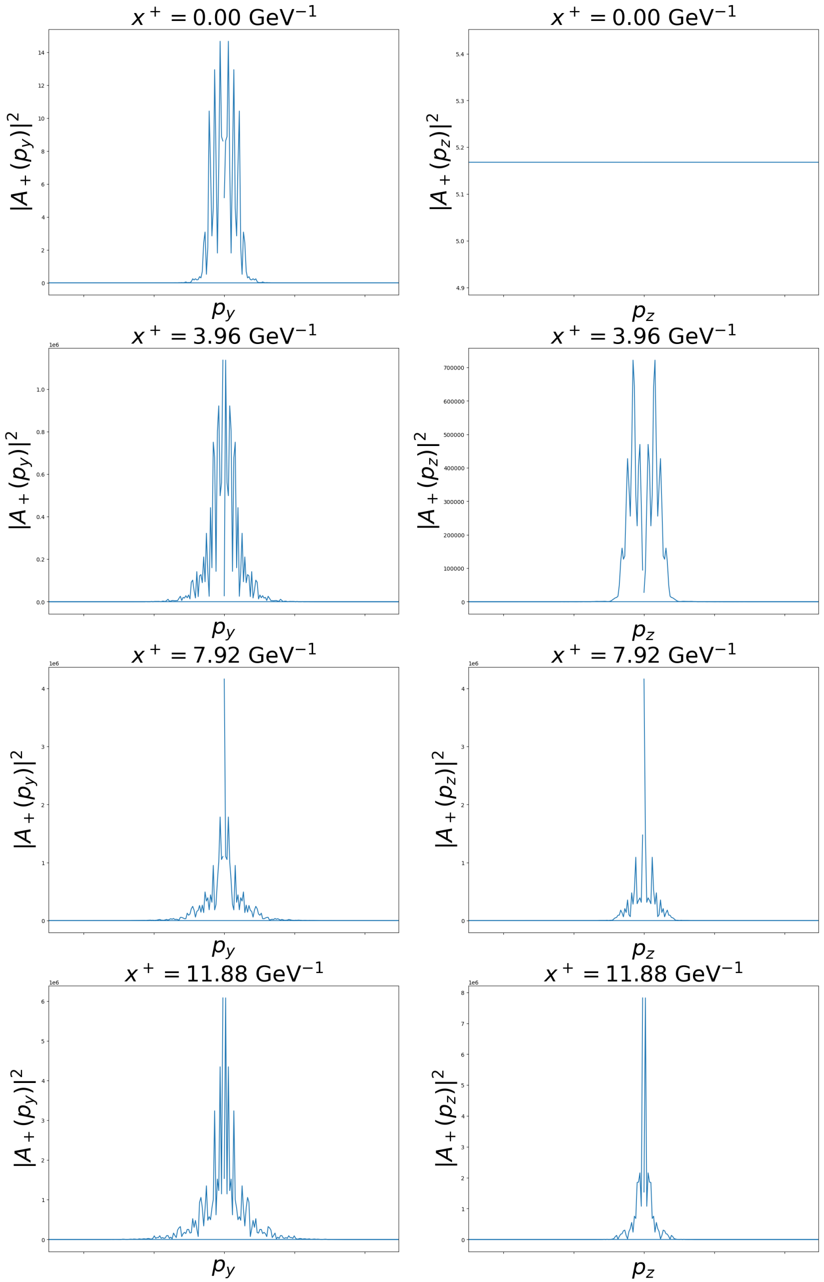


Momentum distribution of the transformed fields

Not setting the field to 0 when $z > t$



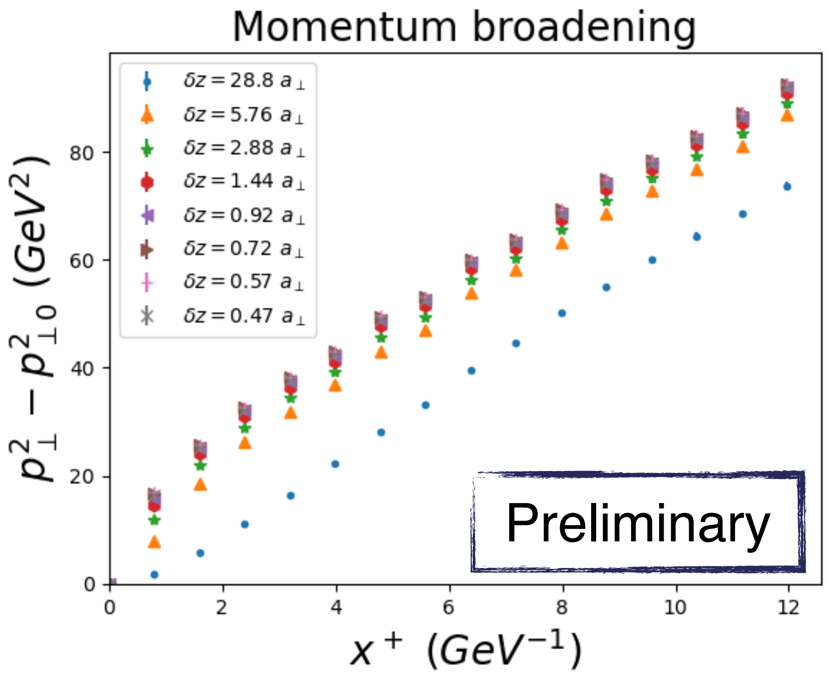
Setting the field to 0 when $z > t$



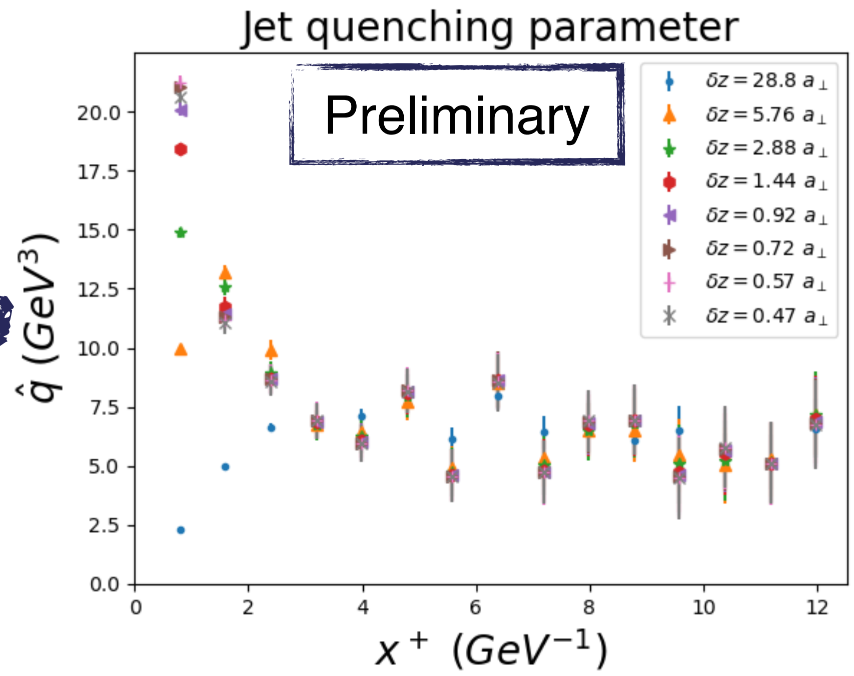
The jet wavepackage width

The jet is no longer a classical object, it is a **Gaussian wavepackage** with position and momentum following uncertainty principle

Results are **independent of the width in** y but very **dependent on the width in** z due to our approximations



$$\hat{q} = \frac{\delta p_\perp^2}{\delta x^+}$$

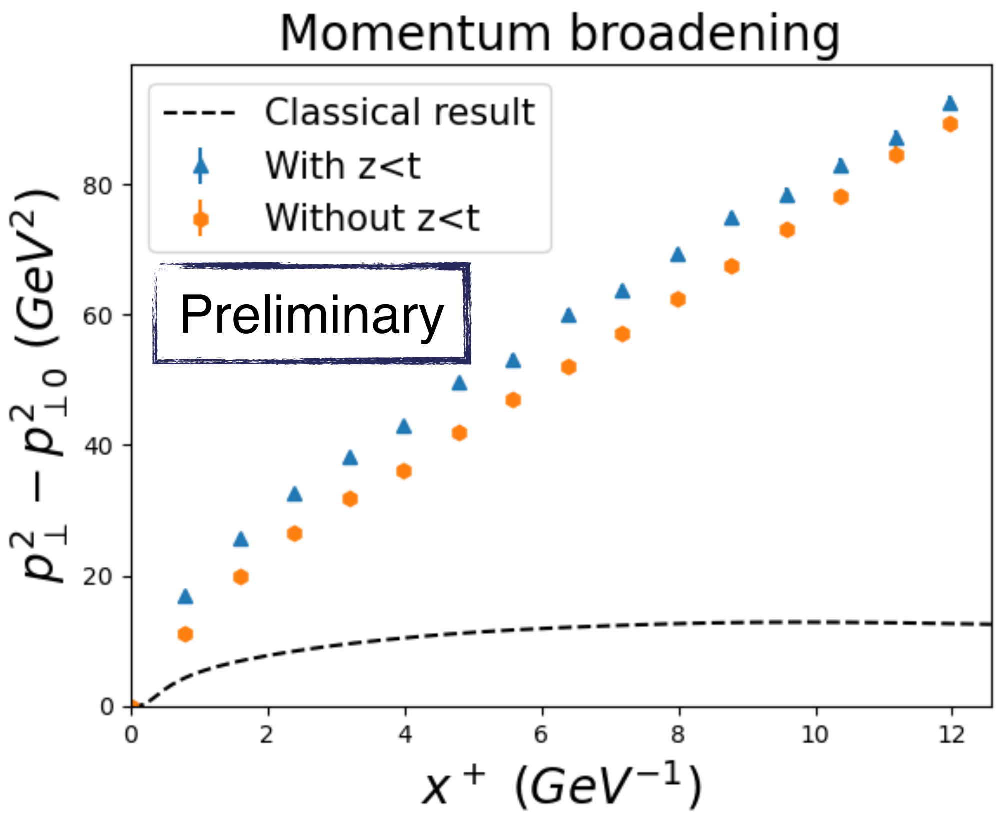


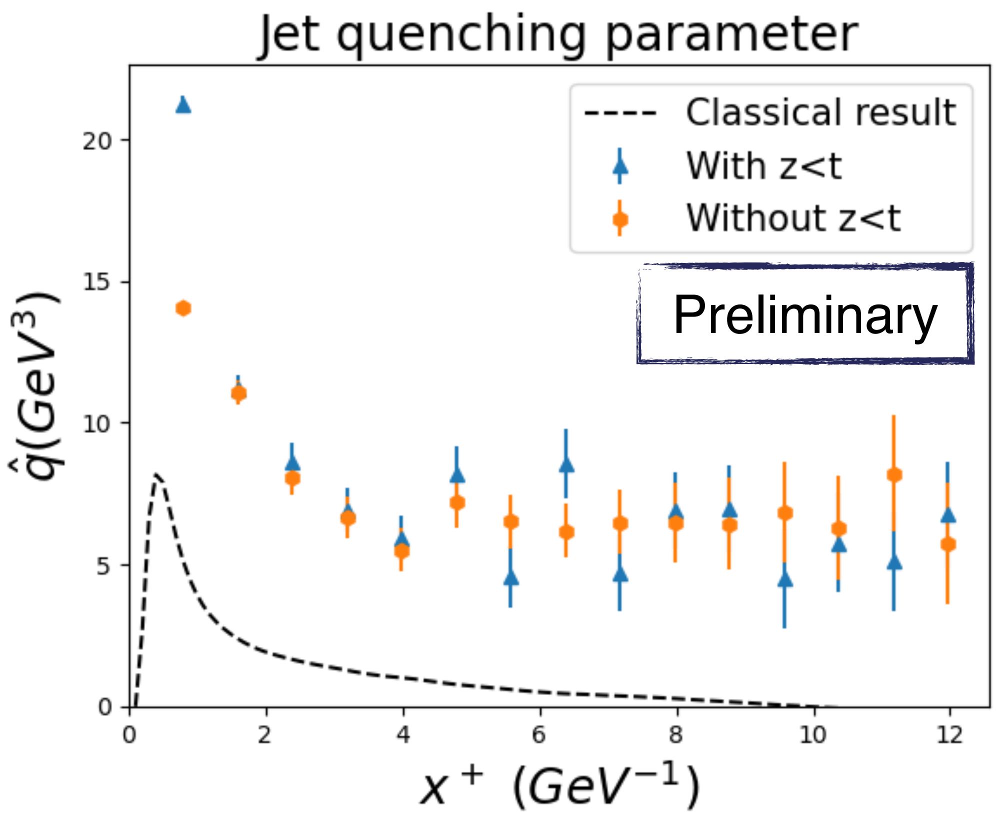
The results for different widths **converge** for jets that are **localized enough**

Long time behavior

The $\hat{q}$ functional form is **similar to the classical simulation**, peaked around initial times, but the **magnitude is larger** [Phys. Lett. B 810 (2020) 135810]

The results are **independent of the imposition of $z < t$** except at very early times

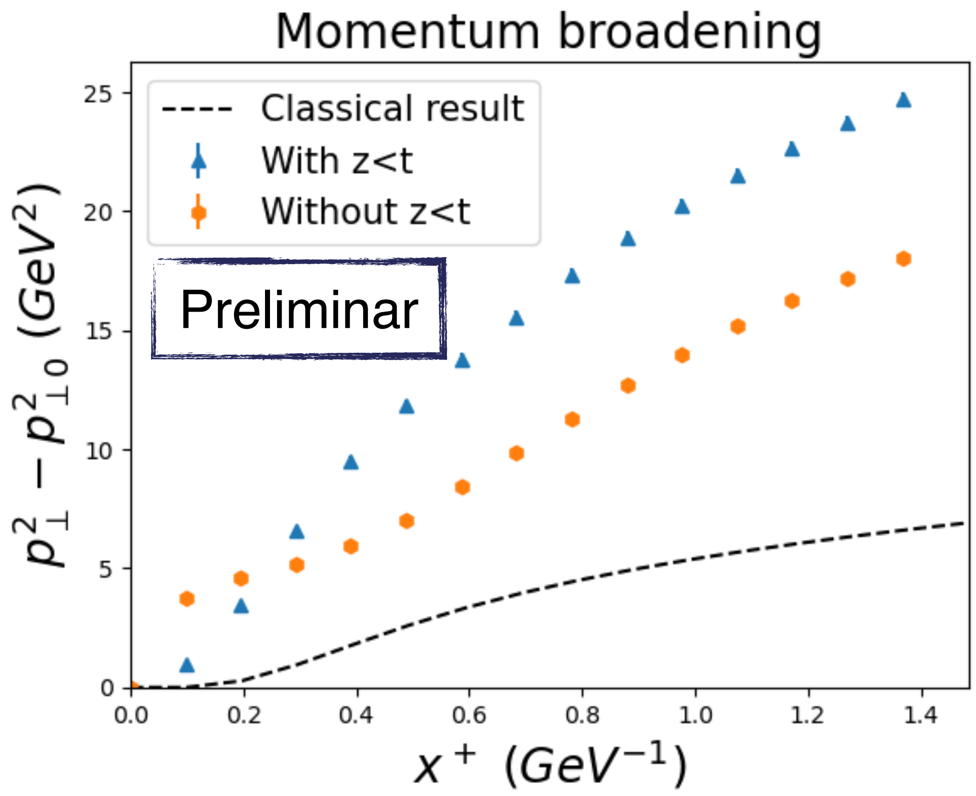


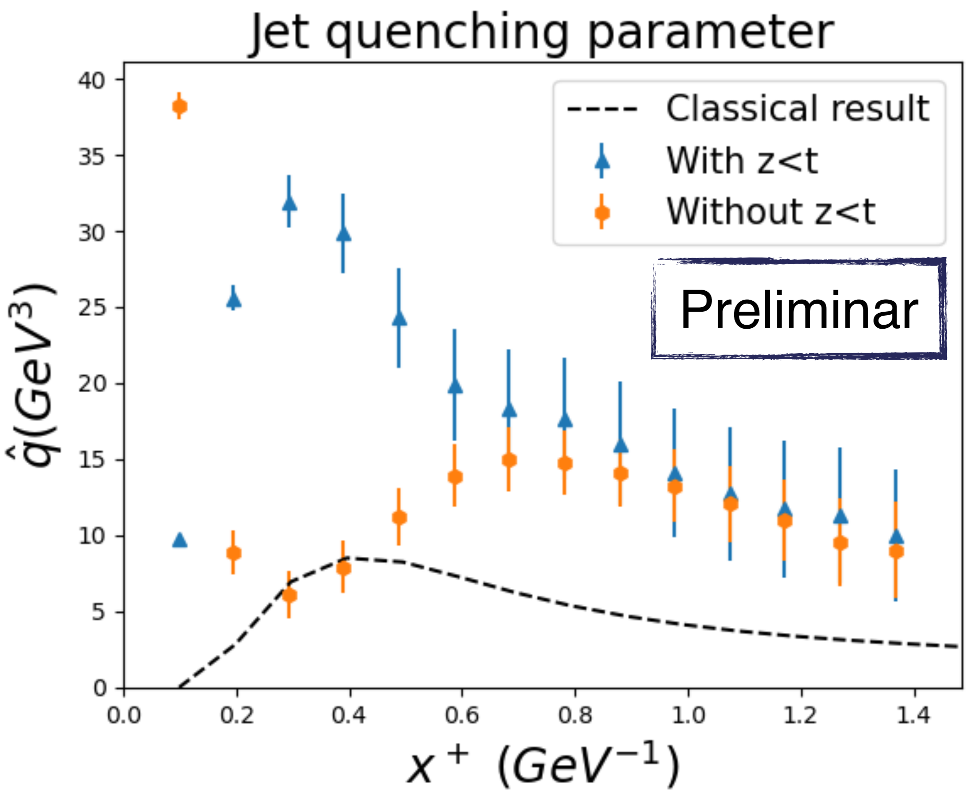


Early time behavior

As the classical result, **peaks at early time** and then **decreases until convergence**

Results are **only sensitive to imposing** $z < t$ for $x^+ < 1\ \mathrm{GeV}^{-1}$, which means $\tau < 1/Q_s$

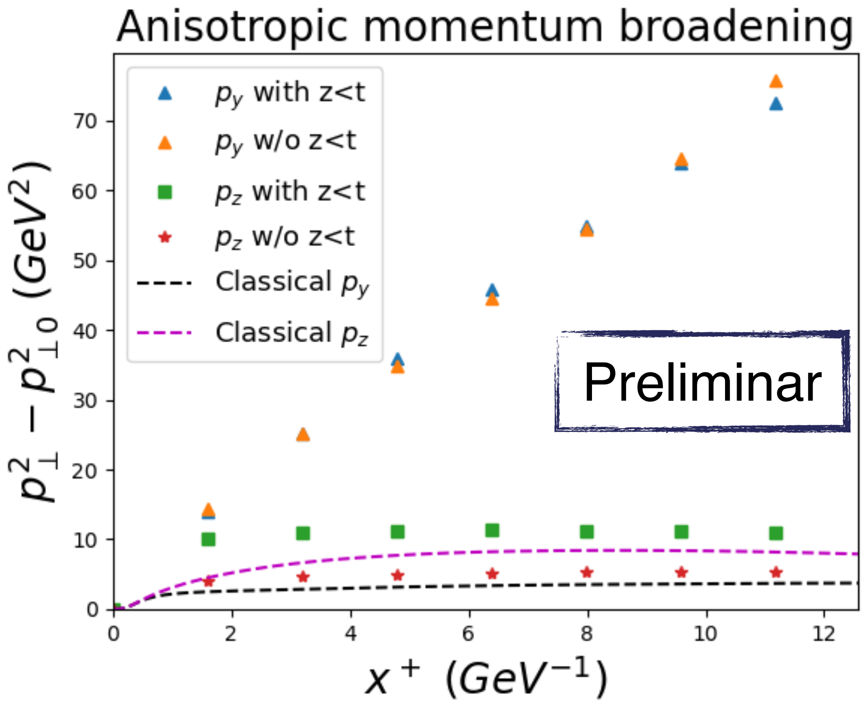




Anisotropic momentum broadening

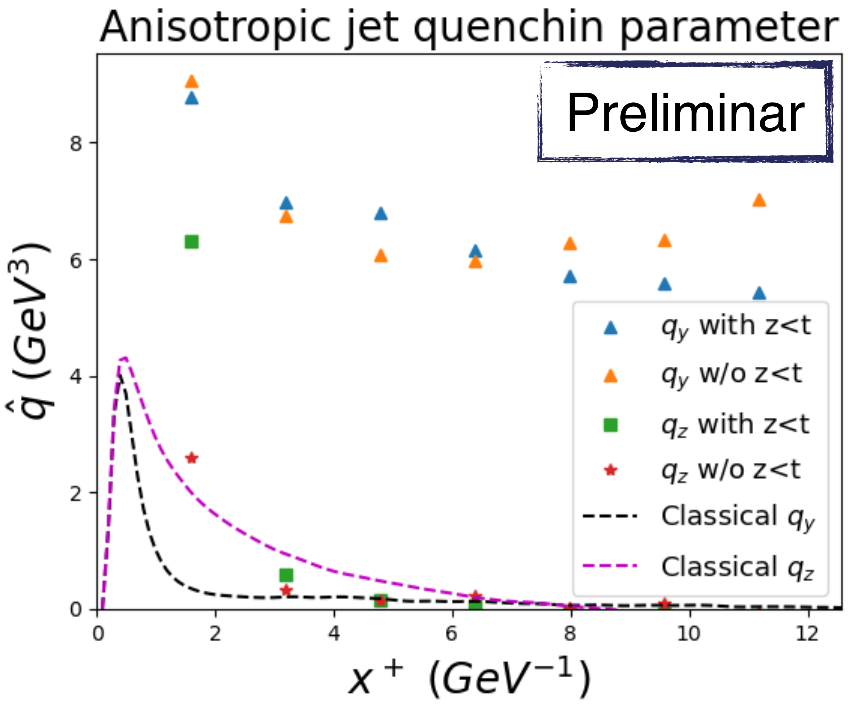
Classical jet results predict a **larger broadening in z**, but quantum jet results predict a **larger broadening in y** at large times

Momentum broadening in y insensitive to $z < t$ but **momentum broadening in z is sensitive** due to the new z dependence introduced by the condition



$\hat{q}_z$ goes to zero for $\tau > 2/Q_s$

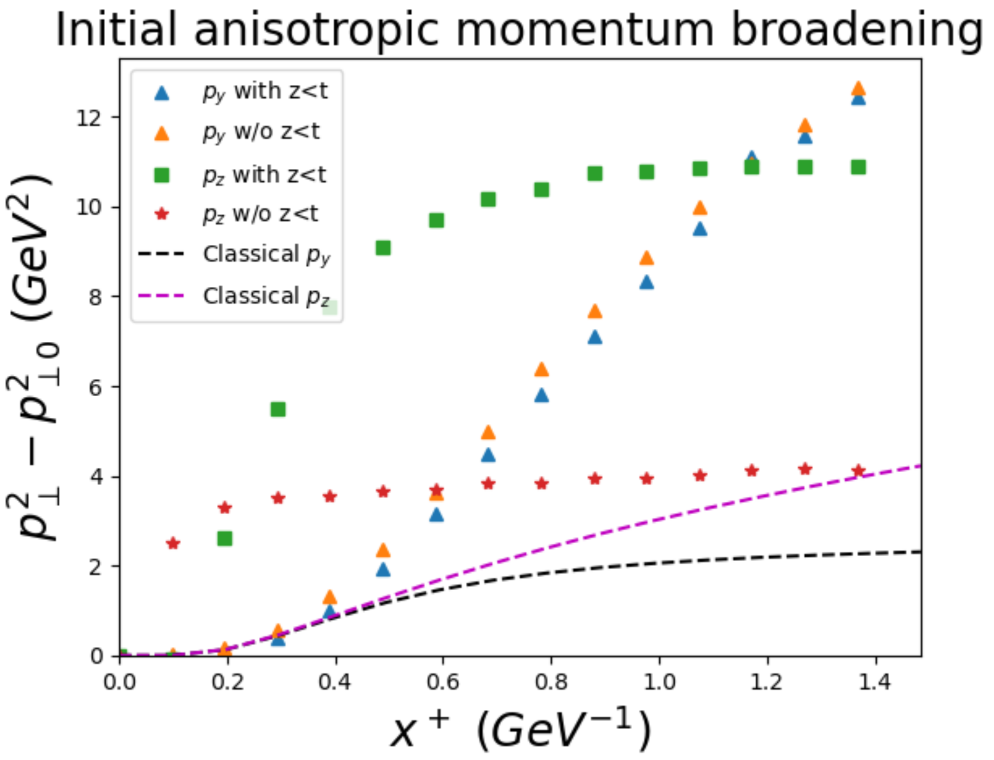
$\hat{q}_y$ remains finite

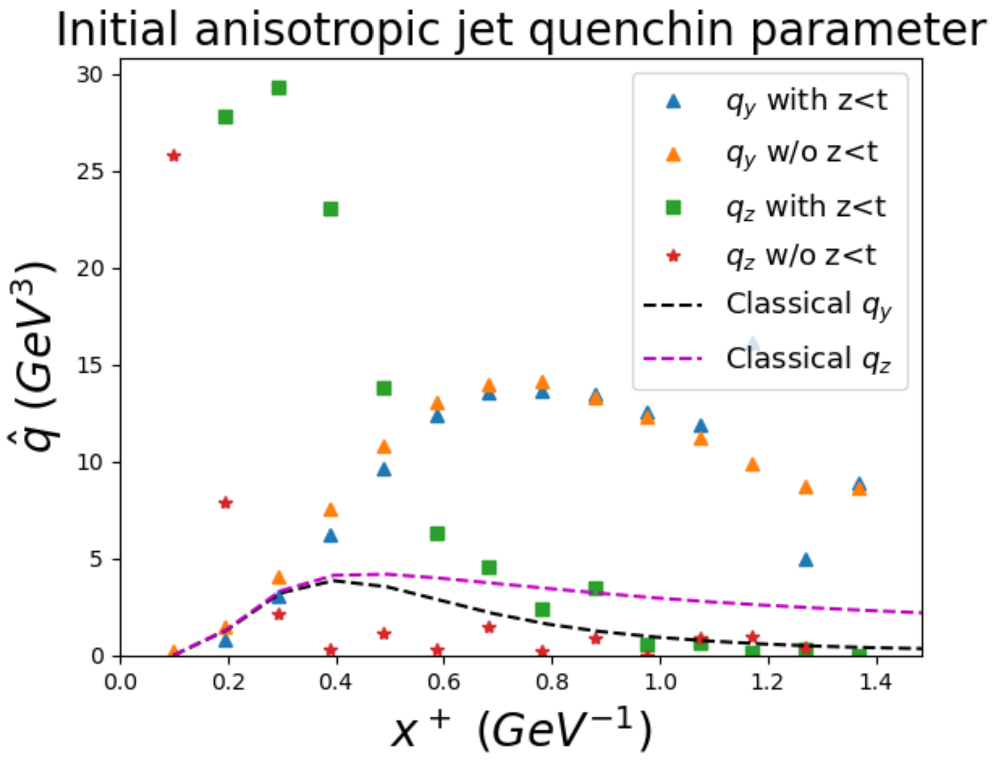


Initial anisotropic momentum broadening

At **very early times momentum broadening is larger along z** component, but $\hat{q}_z$ rapidly decreases until vanishing

Momentum broadening in y insensitive to $z < t$ also at early times





Conclusions…

- Initial stage $\hat{q}$ is **peaked at early times** and then decreases until converging to a constant value
- Momentum broadening is **initially larger along** z direction but is **quickly overcome by broadening along** y
- The **momentum broadening** picked by the jet during the initial stage can indeed be **large**

… and outlook

- More detailed analysis of the early times. How should we **initialize the fields at** $t = 0$? Should we **impose that the fields vanish when** $z > t$?
- Relax the **small z approximation**
- **Include medium induced gluon radiation** in the simulation
- This kind of problem is suitable to a **quantum computing approach**

See Wenyang's talk for quantum computation of jets in heavy-ion collisions

THANKS FOR YOUR ATTENTION!

BACK-UP SLIDES

The Glasma fields initial condition

Imposing **boost invariance**

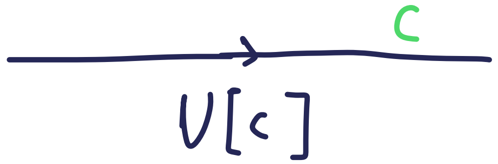
$$A_i^{(3)}(\tau = 0) = A_i^{(1)} + A_i^{(2)} \qquad A^{\eta}(\tau = 0) = \frac{ig}{2}[A_i^{(i)}, A_i^{(2)}]$$

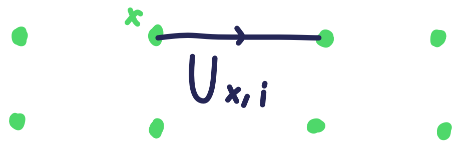
[Phys. Rev. D **52**, 6231]

The real-time lattice gauge theory

Gauge fields — Exponentiation → **Wilson lines** — Discretization → **Gauge links**

$$A_\mu(x) \longrightarrow U[c] = \mathcal{P}\exp\left(-ig\int_c dx^\mu A_\mu(x)\right) \longrightarrow U_{x,\mu} \simeq \left(ig\, a^\mu A_\mu\left(x + \frac{a^\mu}{2}\right)\right)$$





The Gauge transformation

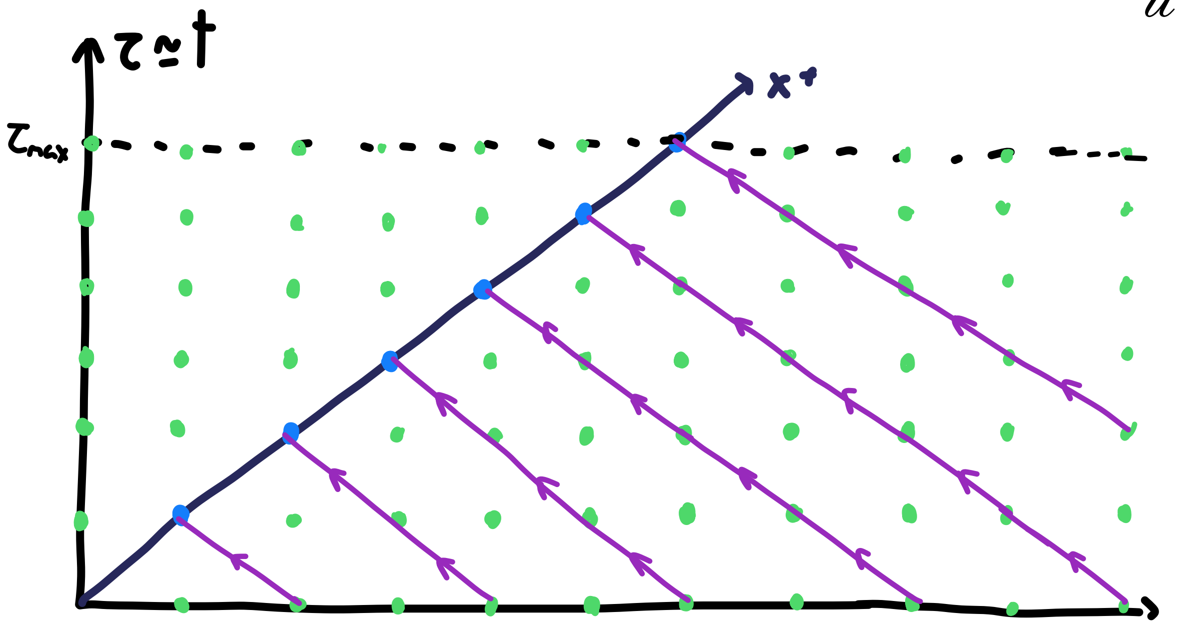
$$\mathcal{U}^{\dagger}_{LC}(x_{LC}) = P\exp\left\{ig\int_{-\infty}^{0} dx^{-}A^{+}_{temp}(x^{+},x^{-},y,z)\right\}$$

Discretizing

$$\mathcal{U}^{\dagger}_{LC}(x^{+},y,z) = \prod_{k}\mathcal{U}^{\dagger}_{LC}(x^{+},x^{-}_{k},y,z)$$

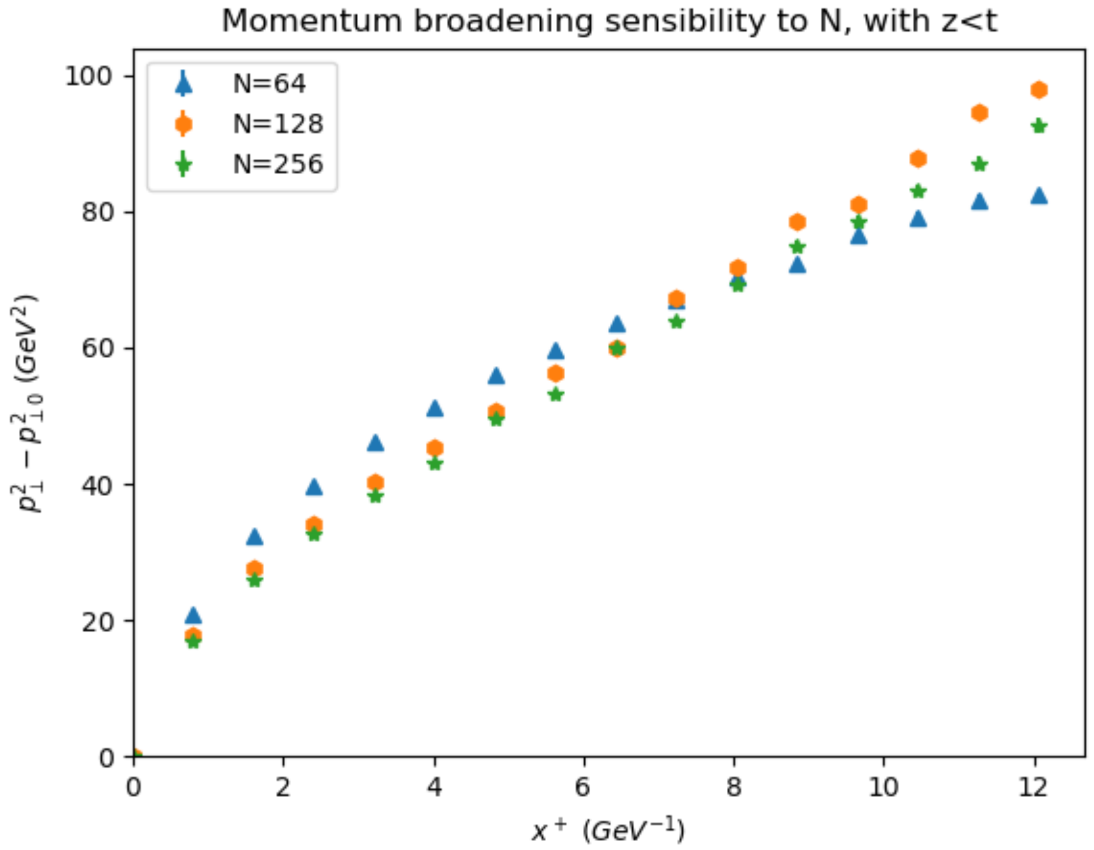
where

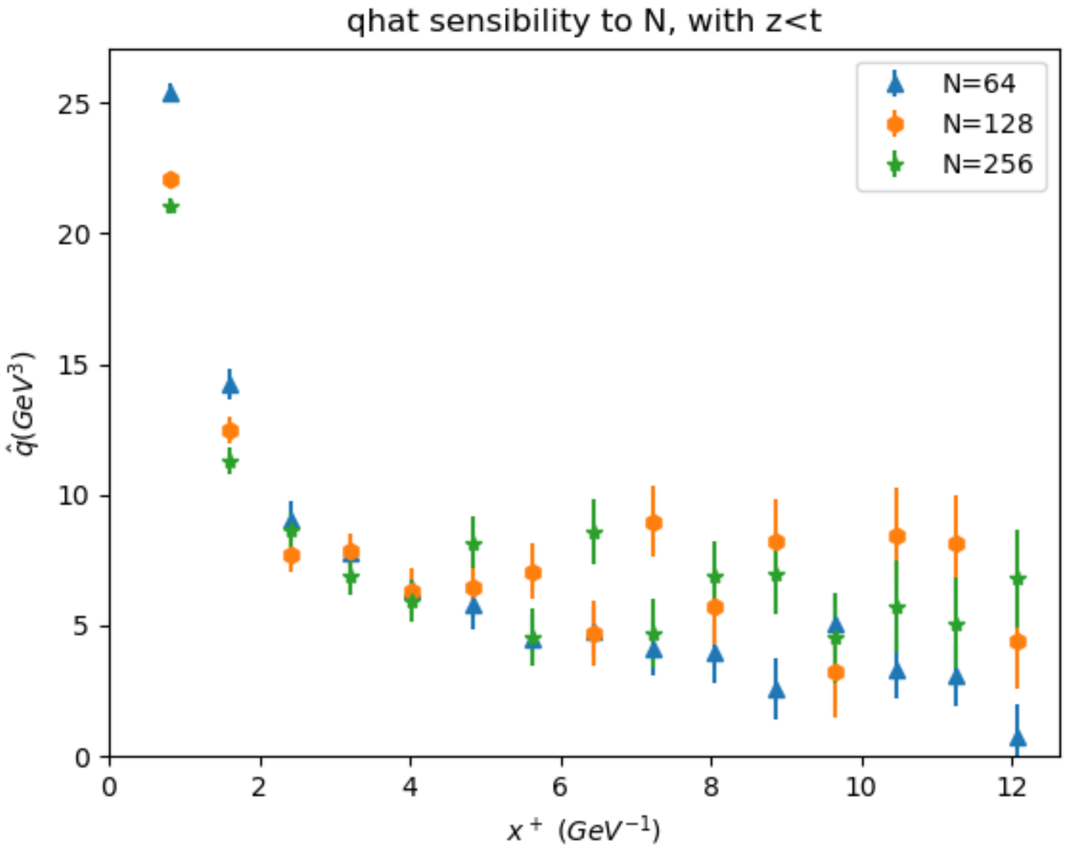
$$\mathcal{U}^{\dagger}_{LC}(x^{+},x^{-}_{k},y,z) = \exp\left\{\frac{za}{\tau^{2}}A^{latt}_{\eta}(x^{+},x^{-},y,z\right\}U_{x}(x^{+},x^{-},y,z)$$



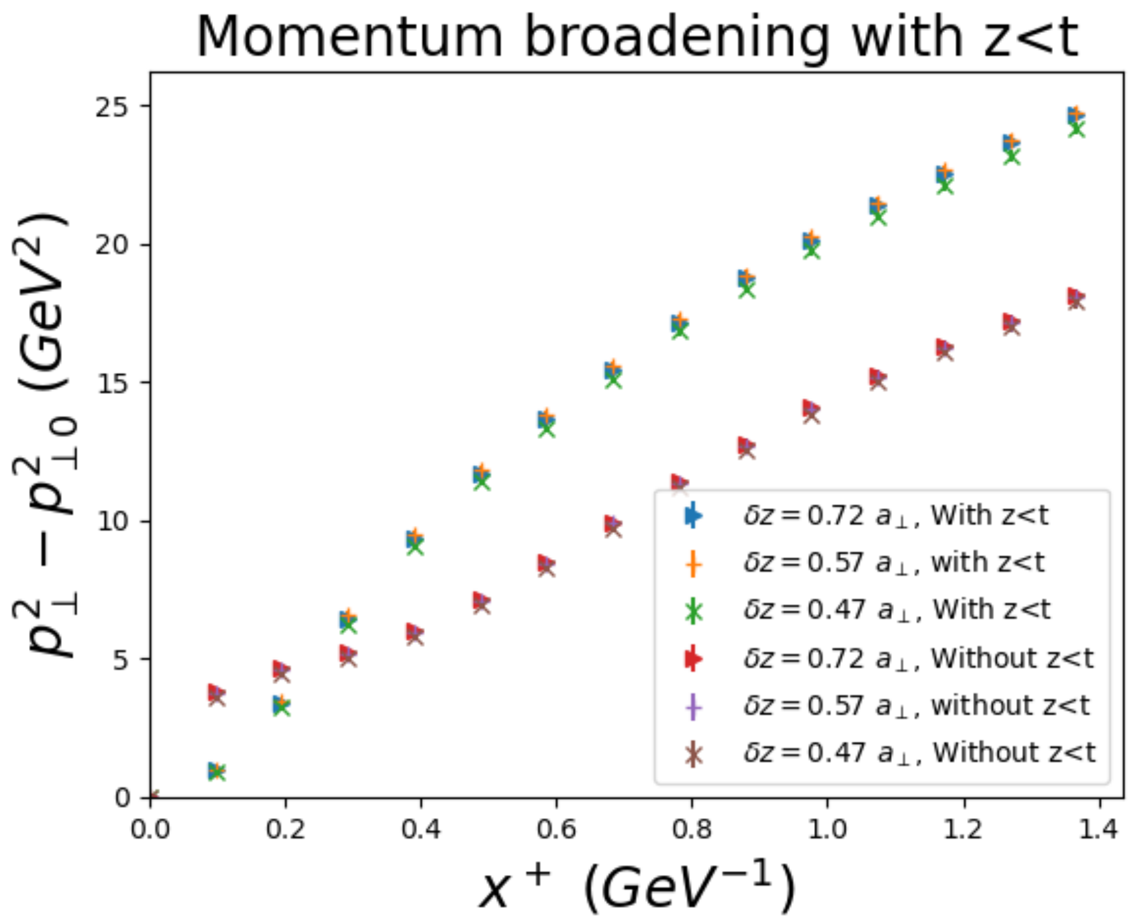
Only z dependence we are considering, restricted to jets at approximately mid-rapidity

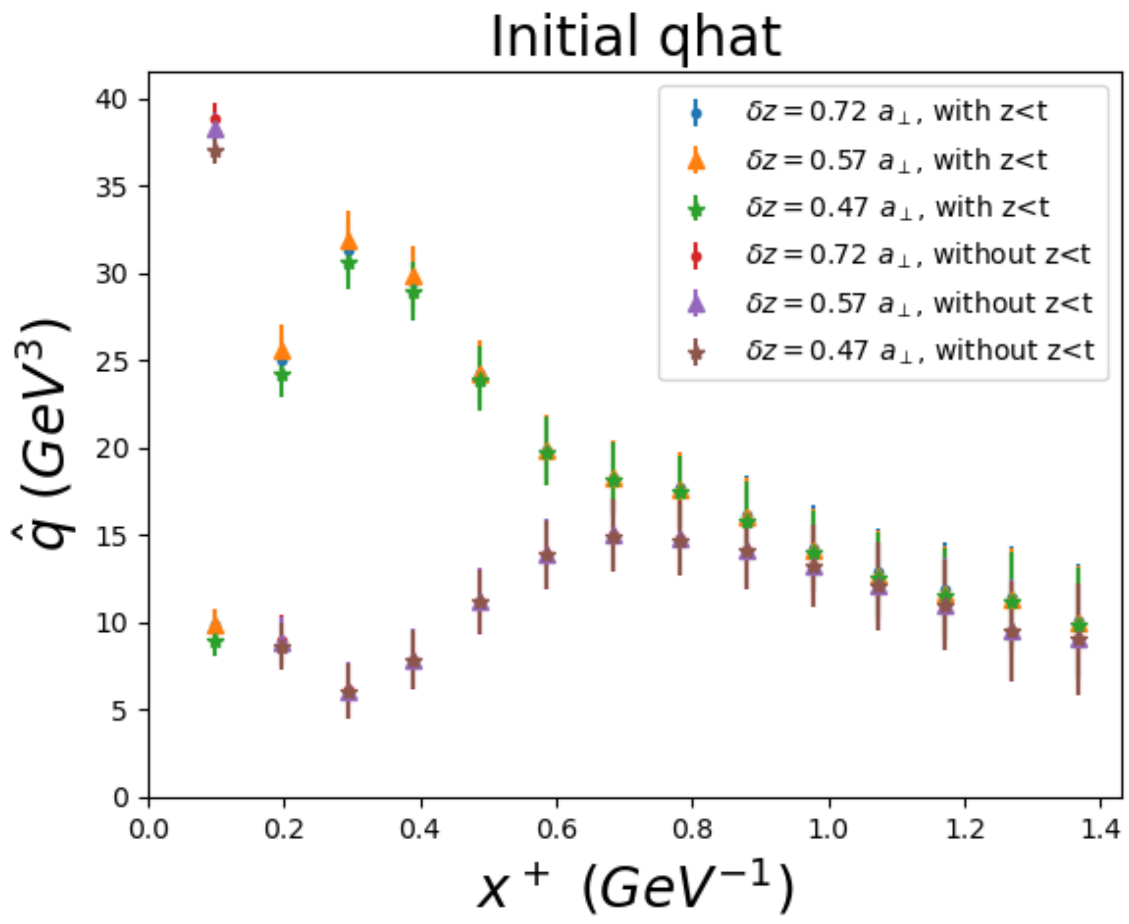
Sensibility to N



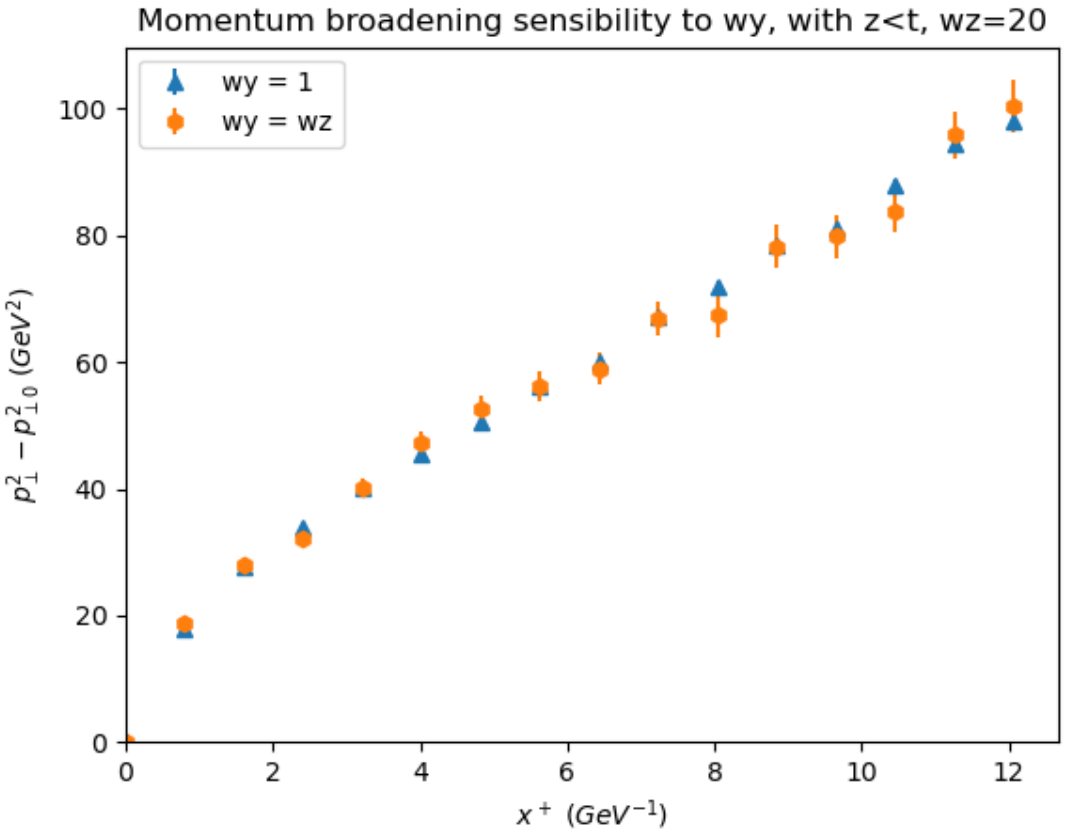


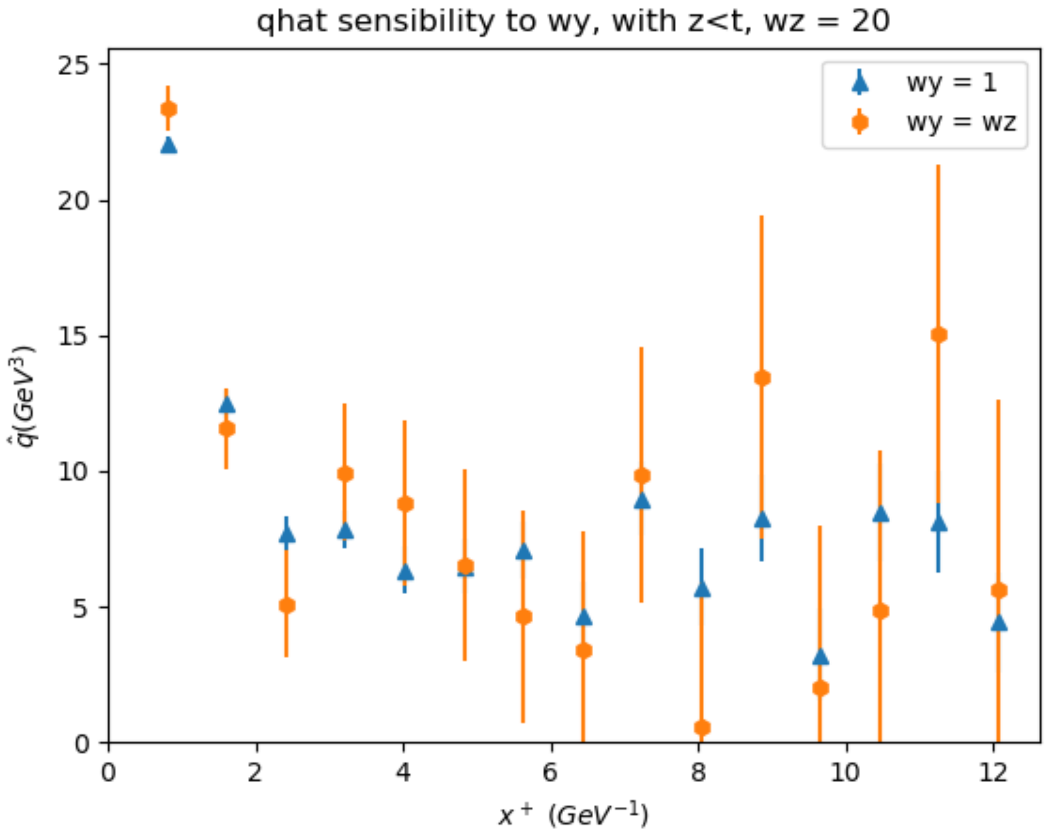
Initial sensitivity to width





Sensitivity to width in y





Simulation parameters

Length: 2.5 fm

Time: 12.25 fm

N = 256

$Q_S = 2\ \text{GeV}$

$Q_S/(g^2\mu) = 0.68$

$m/(g^2\mu) = 0.2$